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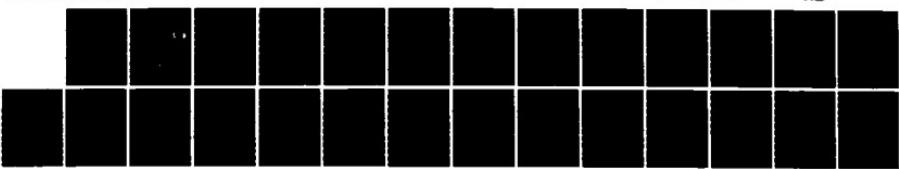
A SIMPLE MODEL OF AEROSOL OPTICAL PROPERTIES IN A
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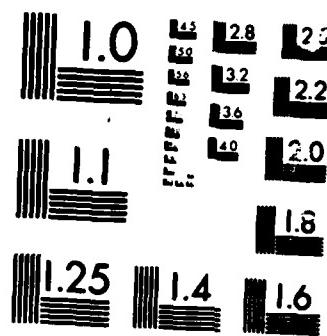
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NRL Memorandum Report 5764

A Simple Model of Aerosol Optical Properties
in a Well-Mixed Marine Boundary Layer
for a Wavelength of $0.50 \mu\text{m}$

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J. W. FITZGERALD

*Atmospheric Physics Branch
Space Science Division*

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A SIMPLE MODEL OF AEROSOL OPTICAL PROPERTIES IN A WELL-MIXED MARINE BOUNDARY LAYER FOR A WAVELENGTH OF $0.50\mu\text{m}$

1 INTRODUCTION

It is well known that absorption and scattering by aerosol particles in the atmosphere has an important effect on radiative transfer and the radiation budget of the earth. The aerosol optical thickness, being the vertically integrated value of extinction due to aerosols, is thus an important parameter affecting climate. Knowledge of the vertical profile of aerosol extinction is also of importance in studies concerned with the performance of the numerous electrooptical systems now in use. These include communications and remote sensing systems and a variety of systems having military applications.

Since the oceans cover roughly three-fourths of the earth's surface, knowledge of aerosol extinction in the marine boundary layer is of obvious importance. An inversion capped convective boundary layer is a fairly common and often persistent feature of the lower atmosphere over many areas of the ocean. The inversion marks the boundary between a turbulent well-mixed layer below and a stably-stratified, non-turbulent free atmosphere above. The structure and evolution of the marine boundary layer is usually modeled by means of mixed layer models (Stage and

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Businger, 1981; Tennekes and Driedonks, 1981; Wakefield and Schubert, 1981). According to these models, the region between the top of the surface layer (~10 m) and the base of the inversion is assumed to be fully mixed with constant values of quantities that are conserved during adiabatic expansion. Davidson et al. (1984) relaxed the zero gradient assumption to permit a small constant gradient of conservative quantities. For a dry convective boundary layer the conserved properties are potential temperature, water vapor mixing ratio and aerosol number concentration (particles per gram of air), while for a cloud-topped mixed layer the conserved quantities are the equivalent potential temperature and the total water mixing ratio.

This paper describes a model of the aerosol optical thickness and the vertical profile of aerosol extinction for the case of a well-mixed marine boundary layer. Presented in the form of both nomograms and analytical approximation formulas, the model predicts the vertical variation of the aerosol extinction coefficient in the boundary layer given the relative humidity, temperature and extinction coefficient at the surface (shipboard level) and the height of the boundary layer. Conversely, given the relative humidity and extinction coefficient at the surface and an estimate of the optical thickness of the boundary layer, the model gives an estimate of the depth of the mixed layer.

Although the model is designed for the cloud-free boundary layer case, it should be quite applicable to a boundary layer containing scattered fair weather cumulus as long as the fractional cloud cover is less than a few tenths.

2 MODEL DESCRIPTION

The aerosol optical thickness of the boundary layer, τ_B , may be written

$$\tau_B = \int_{z_0}^H \beta_e(z) dz, \quad (1)$$

where H is the height of the boundary layer, z_0 is the height of the bottom of the mixed layer and $\beta_e(z)$ is the height-dependent value of the aerosol extinction coefficient. Following Davidson et al. (1984) we take z_0 to be 10 m which coincides approximately with the height of shipboard observations. Eq.(1) may be rewritten as

$$\tau_B = \beta_e(z_0) \int_{z_0}^H [\beta_e(z)/\beta_e(z_0)] dz, \quad (2)$$

where the ratio $\beta_e(z)/\beta_e(z_0)$ is the extinction coefficient at height z normalized to its value at the surface. The extinction coefficient is expressed as

$$\beta_e = \int_0^\infty \pi r^2 Q_e n(r) dr, \quad (3)$$

where $n(r)$ is the number of particles per cm^3 per micron radius interval and Q_e is the extinction efficiency factor computed from Mie theory for spherical homogeneous particles. Since we are assuming well mixed conditions, the change in $n(r)$ with altitude is due mainly to an increase in relative humidity with only a small effect due to the decrease in particle concentrations as a result of the decrease in air density with height.

Vertical profiles of relative humidity for a well-mixed layer are shown in Fig. 1 for various values of surface (i.e., 10 m) relative humidity. A surface temperature of 75°F was assumed. Relative humidity is defined as the quotient of the observed water vapor mixing ratio to the saturation mixing ratio:

$$S = \frac{m}{m_s} \quad (4)$$

Percent relative humidity (RH) is S times 100. The saturation mixing ratio is a function of both temperature and pressure and is defined as

$$m_s = \frac{0.622e_s}{P - e_s},$$

where e_s is the saturation vapor pressure and P is atmospheric pressure. In computing the relative humidity

profiles shown in Fig. 1 it was assumed that m is constant with height, that temperature decreases at the dry adiabatic lapse rate, $\Gamma_a = -9.76^\circ\text{C}/\text{km}$ and, therefore, that pressure changes according to

$$\frac{P}{P_0} = \left(\frac{T}{T_0}\right)^\alpha, \quad (5)$$

where P_0 and T_0 are the pressure and temperature at the surface and $\alpha = g/R_d\Gamma_a = 3.497$. Here g is the acceleration of gravity and R_d is the gas constant of dry air.

Vertical profiles of the normalized extinction coefficient, $\beta_e(z)/\beta_e(z_0)$, were computed from the relative humidity profiles in Fig. 1 and a model of aerosol extinction as a function of relative humidity. The dependence of aerosol extinction on relative humidity was calculated from Eq. (3) using the model of particle size versus relative humidity shown in Fig. 2 and the marine aerosol size distribution shown in Fig. 3. This size distribution is a smooth fit to a size distribution that was measured approximately 600 km off the east coast of the U.S. on March 13, 1983 during a cruise of the USNS Lynch. Particles smaller than $0.5\mu\text{m}$ were measured with the NRL differential mobility analyzer while particles larger than $0.6\mu\text{m}$ were measured with a gelatin replication impactor (Calspan Corp.). The relative humidity at the time of the measurements was 52%.

Fig. 2 shows the ratio of particle radius at a given humidity to particle radius in dry state plotted as a function of relative humidity. Particles smaller than $0.5\mu\text{m}$ are assumed to grow according to curve 1 while particles larger than $1.5\mu\text{m}$ are assumed to follow growth curve 2. The growth curve of intermediate sized particles is assumed to lie between these two curves. Growth curve 1 assumes that particles are 90% soluble, the soluble material being a mixture of ammonium sulfate and ammonium nitrate. It is based on the measurements of Hanel and Lehmann (1981) of the water uptake as a function of relative humidity by samples of atmospheric aerosol material that contained these two salts as the primary water-soluble constituents. This growth model for the smaller marine aerosol particles is consistent with recent measurements (Hoppel et al., 1985) of the volatility of submicron particles over the Pacific. In these experiments, particles were subjected to a level of heating that would evaporate the more volatile aerosol components without affecting the highly involatile sea-salt component. It was found that nearly all the particles were highly volatile, indicating that they likely were composed of gas-phase conversion products such as sulfates and nitrates. Curve 2, describing the growth of the larger particles, is the mean of Hanel's (1976) sea spray aerosol growth model (Hanel's model 2) and his model 3 for maritime aerosols over the Atlantic. In obtaining curve 2, we

averaged the growth curves for increasing and decreasing relative humidity.

In computing the growth curves, the effect of particle curvature on the equilibrium relative humidity was neglected so that the curves are strictly valid for infinitely large particles. The error in r/r_d due to the neglect of particle curvature is less than about 5% for $r_d > 0.1\mu\text{m}$ and $\text{RH} \leq 97\%$. Furthermore, since particles smaller than $0.1\mu\text{m}$ contribute less than a few percent to the extinction coefficient at $0.5\mu\text{m}$ for typical marine aerosol size distributions, the resulting error in the computed variation of aerosol extinction with relative humidity is quite small.

Fig. 4 shows the calculated variation of aerosol extinction with relative humidity for a wavelength of $0.50\mu\text{m}$. The results are presented as a plot of the normalized extinction coefficient as a function of relative humidity. The dependence of the normalized extinction on relative humidity is determined primarily by the aerosol growth model assumed (i.e., on aerosol composition) and depends only weakly on the particle size distribution. We computed the normalized extinction for a number of size distributions measured on the 1983 cruise, including a typical distribution for the remote tropical Atlantic, and found a maximum variation of $\beta_e(\text{RH})/\beta_e(\text{RH}=52\%)$ of about 20% at 97% relative humidity with a smaller variation at lower humidities.

From the variation of relative humidity with height (Fig. 1) and the variation of extinction with relative humidity (Fig. 4) we computed the profiles of normalized aerosol extinction shown in Fig. 5. The abscissa is the aerosol extinction at height z divided by the aerosol extinction at the surface (10-m level). Each curve is for a different value of surface relative humidity as identified in the key. Thus, if we know the aerosol extinction coefficient and relative humidity at the surface and the height of the boundary layer, then Fig. 5 can be used to obtain the profile of aerosol extinction within the boundary layer. The accuracy of the predicted profile of aerosol extinction depends on the accuracy to which the extinction coefficient and relative humidity at the surface can be determined. The aerosol extinction coefficient at the surface can be obtained from direct measurements of the scattering or extinction coefficient, from visibility measurements via the Koschmieder formula (i.e., $V=3.91/\beta_e$) or from Mie calculations using a predicted or measured surface aerosol size distribution.

The profiles of the normalized aerosol extinction coefficient in Fig. 5 were computed only up to the height at which the relative humidity reached 97%. There are two principal reasons why the profiles are truncated at this

height. First, since the vertical resolution of temperature and humidity profiles obtainable with standard radiosondes is only about 150 feet, the height of the boundary layer can only be resolved to within 150 feet or so. Within a distance of 150 feet the relative humidity would increase from 97% to almost 100% and the extinction would change by a factor of about three. Thus, in cases when the relative humidity at the top of the cloud-free (or mostly cloud free) boundary layer is above 97%, uncertainties in determining the height of the boundary layer can lead to large errors in the predicted aerosol extinction coefficient. Second, if the boundary layer is deep enough for the relative humidity to exceed 97% then there is a good chance that the boundary layer will be cloud covered and that the optical properties in the region between the 97% humidity level and cloud base will be affected by the presence of the clouds (e.g., through turbulent mixing at cloud base).

Eq. (2) shows that the aerosol optical thickness of the boundary layer can be expressed as the product of the extinction coefficient at the surface and the vertically integrated value of $\beta_e(z)/\beta_e(z_0)$. The integral in Eq. (2) was evaluated using the profiles of aerosol extinction given in Fig. 5. Fig. 6 is a plot of this integral as a function of boundary layer height, H, for various values of surface relative humidity. The key in Fig. 5 identifies the values

of surface relative humidity corresponding to each curve. The dashed curve in Fig. 6 gives the value of the integral if there were no change in aerosol extinction with height. In this case the integral simply has the value $H - z_0$. To estimate the optical thickness of the boundary layer we use Fig. 6 to obtain the appropriate value of the integral in Eq. (2) and then multiply this value by the aerosol extinction coefficient at the surface.

3 ANALYTICAL MODEL

Although the nomograms (Figs. 5 and 6) are very useful, interpolation is required for other values of surface relative humidity. It is clearly advantageous to have an analytical form of the model to facilitate computer calculations of the aerosol extinction profile. One such model is developed below.

Relative humidity may be calculated from temperature T and dew point T_d by means of the expression

$$S = \exp \left[\frac{19.5 (T_d - T)}{269.9 + T + T_d} \right], \quad (6)$$

where S is the saturation ratio and T and T_d are in $^{\circ}\text{C}$. This expression is identical to the one developed by Shettle (1978) except that in Shettle's original expression the

coefficient of $T_d - T$ in the numerator is 19.772. Shettle's approximation has a RMS error of 0.11% for $0 \leq (T - T_d) \leq 40^\circ\text{C}$. Near the ocean surface one is normally dealing with a smaller range of $T - T_d$.

Denoting the values of T and T_d at shipboard height ($z = z_o$) by T_o and T_{do} we have, assuming adiabatic mixing,

$$T(z) = T_o + \Gamma_a(z - z_o) \quad (7)$$

$$T_d(z) = T_{do} + \Gamma_{da}(z - z_o),$$

where Γ_a and Γ_{da} are the adiabatic lapse rates of temperature and dew point, respectively. We take $\Gamma_{da} = -.00175^\circ\text{C/m}$ and $\Gamma_a = -.00976^\circ\text{C/m}$.

Combining Eqs. (6) and (7) yields

$$S(z) = \exp \left[\frac{19.5(T_{do} - T_o) + .156(z - z_o)}{269.9 + T_o + T_{do} - .0115(z - z_o)} \right], \quad (8)$$

where $S(z)$ is the saturation ratio at height z . Eq. (8) gives the relative humidity at height z as a function of the temperature and dew point at the surface. The surface dew point temperature can be computed from the relative humidity and temperature at the surface using

$$T_{do} = \frac{19.5T_o + (269.9 + T_o) \ln S_o}{19.5 - \ln S_o}, \quad (9)$$

where S is the saturation ratio at the surface.

The dependence of aerosol extinction on relative humidity given in Fig. 4 can be approximated by the expression

$$\frac{\beta_e(S)}{\beta_e(S=.52)} = \left[1 + \frac{S - .52}{1.017 - S} \right]^{.84} \quad (10)$$

This equation is accurate to within 10% in the range $0.73 < S < 0.82$ and to within 1% to 5% for values of S outside this range. The ratio of extinction at relative humidity S_2 to that at relative humidity S_1 , where $S_2 > S_1 \geq 0.52$, may be written

$$\frac{\beta_e(S_2)}{\beta_e(S_1)} = \frac{\beta_e(S_2)}{\beta_e(S=.52)} / \frac{\beta_e(S_1)}{\beta_e(S=.52)} = \frac{\left[1 + \frac{S_2 - .52}{1.017 - S_2} \right]^{.84}}{\left[1 + \frac{S_1 - .52}{1.017 - S_1} \right]^{.84}}$$

which reduces to

$$\frac{\beta_e(S_2)}{\beta_e(S_1)} = \left[\frac{1.017 - S_1}{1.017 - S_2} \right]^{.84} \quad (11)$$

Substituting $S(z)$ for S_2 and S_0 for S_1 in Eq. (11) yields

$$\beta_e(z) = \beta_e(z_0) \left[\frac{1.017 - S_0}{1.017 - S(z)} \right]^{.84} \quad (12)$$

Profiles of aerosol extinction in the marine boundary layer can be computed from Eqs. (8), (9) and (12) provided we know the height of the boundary layer, and the temperature, relative humidity and extinction coefficient at the surface.

The extinction coefficient at height z can be adjusted for the decrease in particle number density (particles per cm^3) with height resulting from the decrease in air density by multiplying the right side of Eq. (12) by $\rho(z)/\rho(z_0)$, which is the ratio of the density of air at height z to the density of air at the surface. The change in air density with altitude may be approximated by

$$\rho(z)/\rho(z_0) = e^{-Az}$$

where $A = 7.94 \times 10^{-5} \text{ m}^{-1}$.

4 SUMMARY

A simple model to predict the vertical profile of aerosol extinction and the aerosol optical thickness in the marine boundary layer is presented. The model assumes that the boundary layer is well mixed, so that the potential temperature, water vapor mixing ratio and dry aerosol size distribution are constant with height from the 10-m level (shipboard level) to the inversion. Required inputs to the model are the temperature, relative humidity (or dew point) and extinction coefficient at the surface and the height of

the boundary layer. Particles larger than $1.5\mu\text{m}$ radius are assumed to grow with relative humidity according to curve 2 in Fig. 2. This curve is a mean between Hanel's (1976) growth model 2 (sea spray aerosols) and model 3 (maritime aerosol over the Atlantic). Particles smaller than $0.5\mu\text{m}$ follow growth curve 1 which describes the behavior of particles which are 90% soluble, the soluble component consisting of ammonium sulfate and ammonium nitrate. Intermediate sized particles have a growth curve between curves 1 and 2, reflecting a transition from particles composed primarily of gas-to-particle conversion material to sea salt particles.

The model is presented in two forms: (1) Nomograms (Figs. 5 and 6) which give the ratio of the aerosol extinction coefficient at height z to aerosol extinction at the surface (Fig. 5) and the vertically integrated value of aerosol extinction as a function of boundary layer height and surface relative humidity (Fig. 6) and (2) Analytical approximation formulas [Eqs. (8), (9) and (12)] from which one can compute aerosol extinction as a function of height given the required input values.

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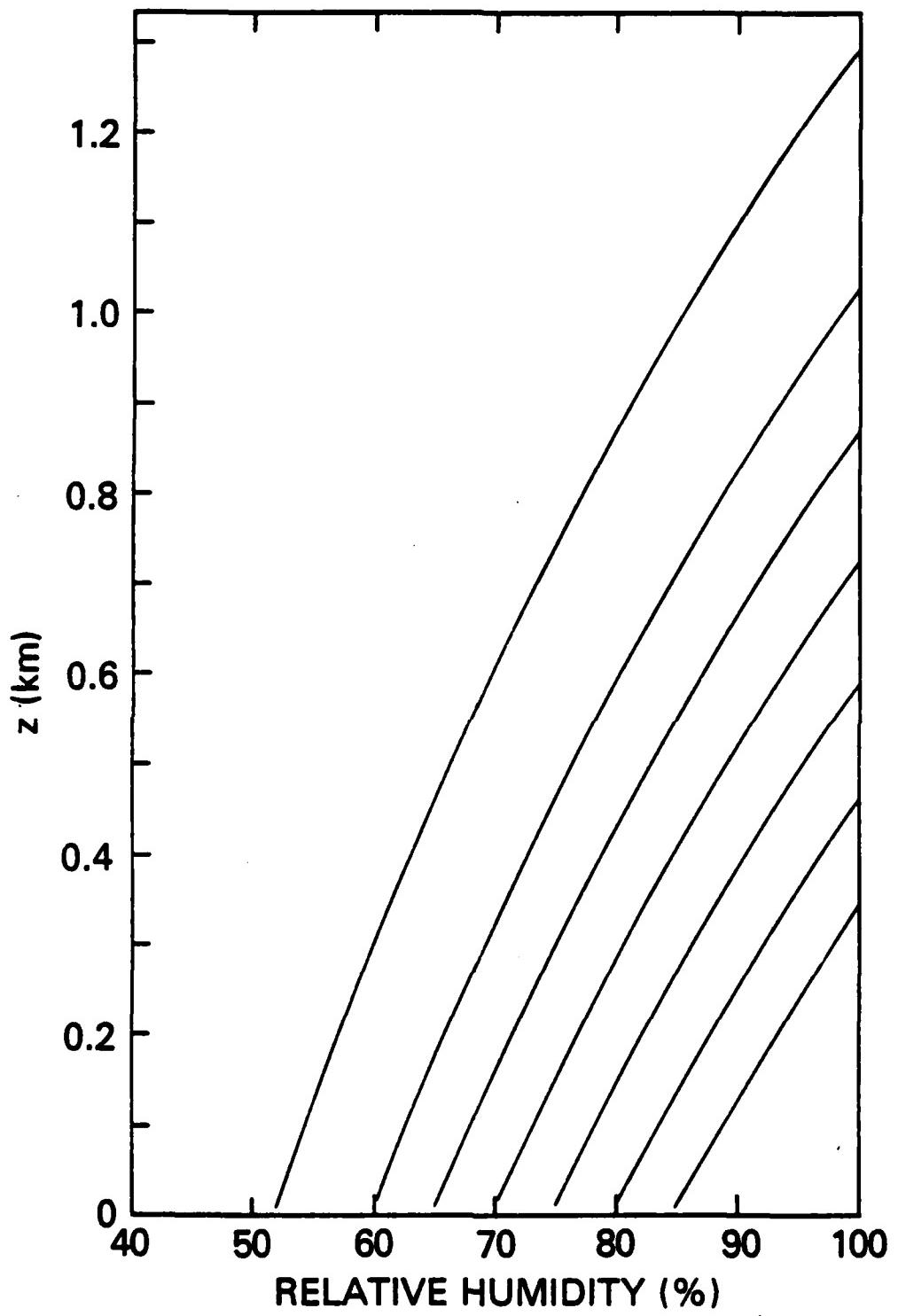


Figure 1 Vertical profile of relative humidity for a well-mixed boundary layer.

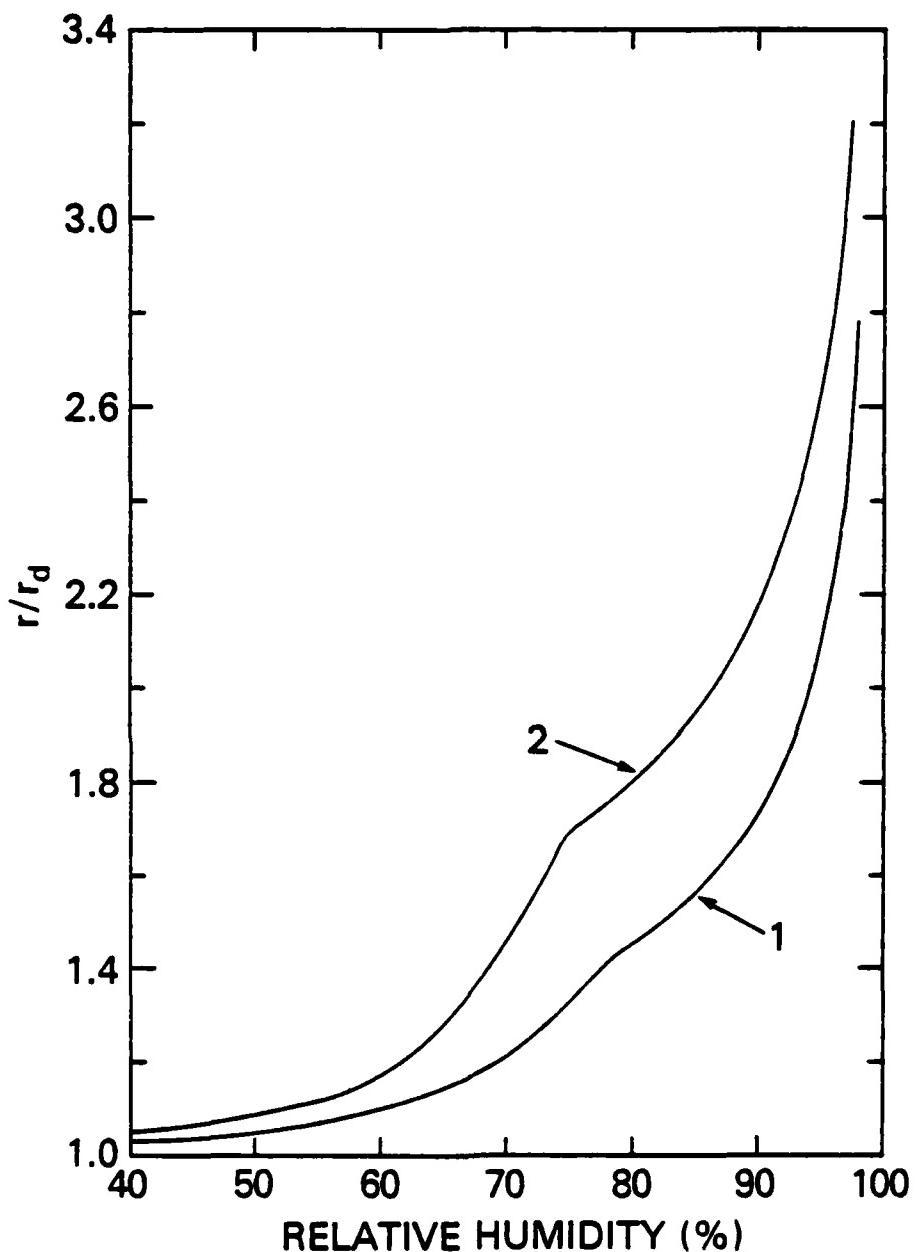


Figure 2 Models of particle size as a function of relative humidity used in the calculations. Curve 1 is for particles smaller than $0.5\mu\text{m}$ radius while curve 2 is for particles larger than $1.5\mu\text{m}$.

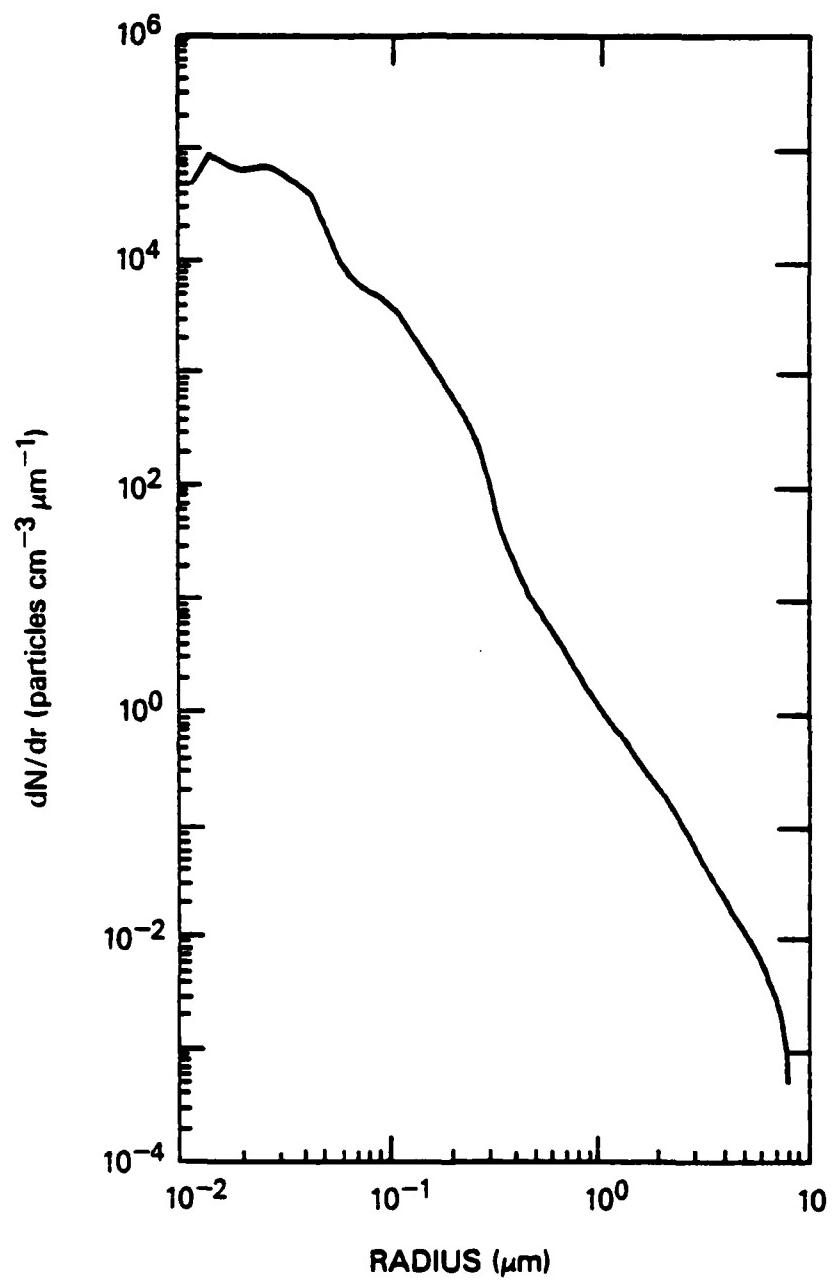


Figure 3 Particle size distribution used in conjunction with particle growth curves to compute aerosol extinction as a function of relative humidity.

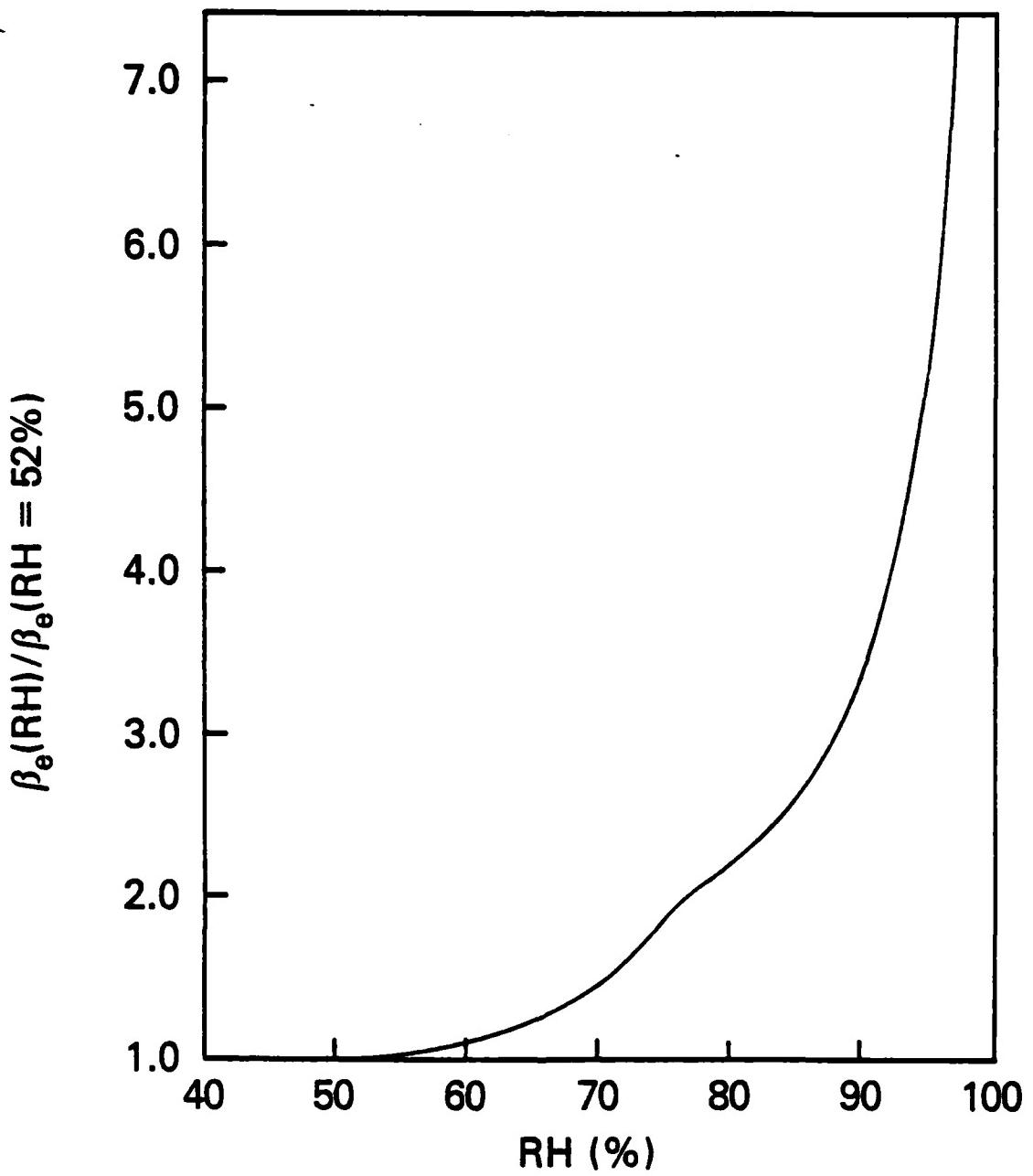


Figure 4 Calculated variation of aerosol extinction with relative humidity for a wavelength of $0.5\mu\text{m}$.

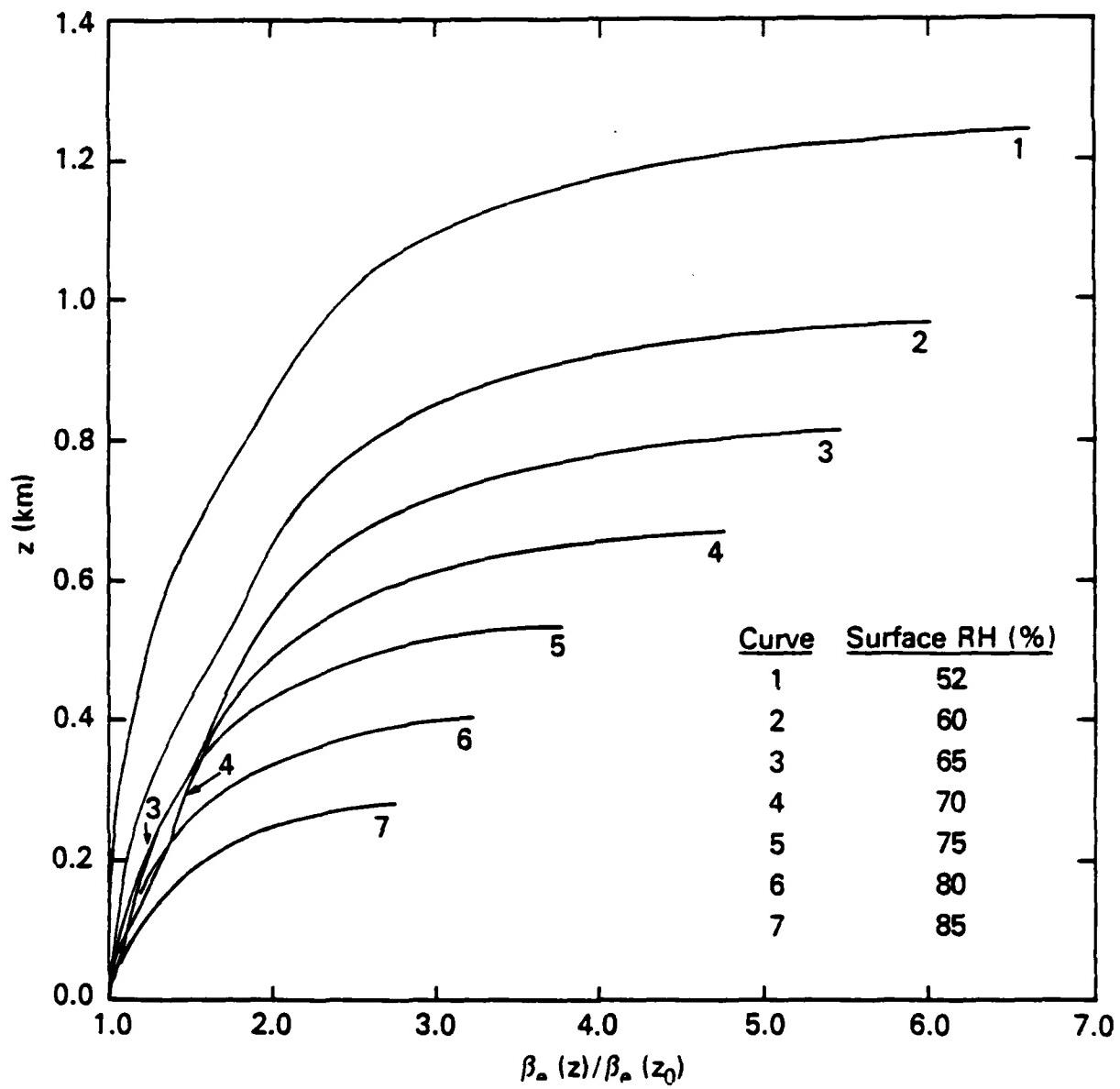


Figure 5 Ratio of the aerosol extinction coefficient at height z to aerosol extinction at the surface, plotted as a function of z . Each curve is for a different value of surface relative humidity as identified in the key.

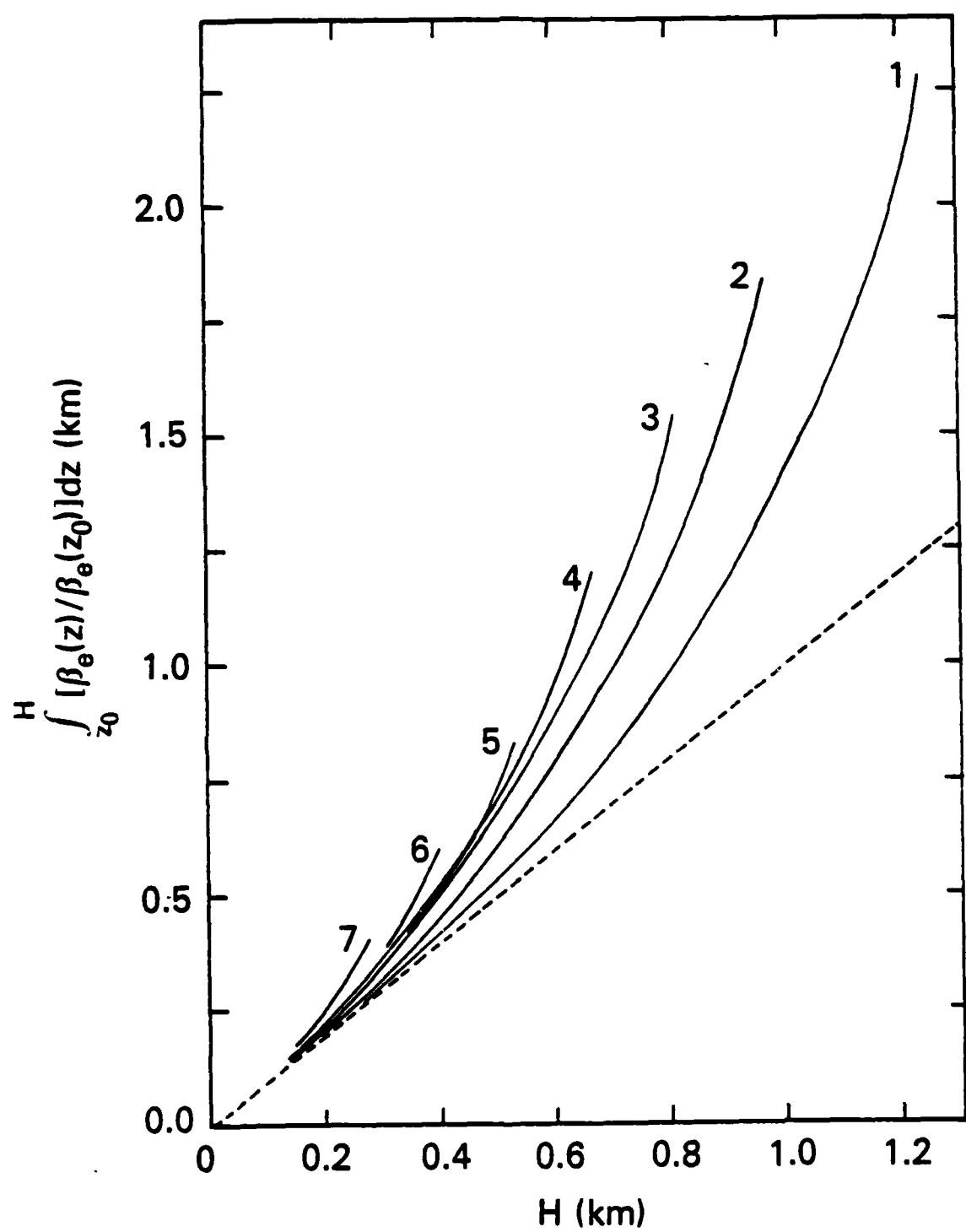


Figure 6 The value of the integral in Eq. (2) plotted as a function of boundary layer height, H , for various values of surface relative humidity. [See Fig. 5 for a key to the curves].

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